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(NASA CR-51425) OTS;

ATTN: Mr. Roland H. Chase, Technical Director
Code RET

Subject: MIROS Progress Letter No. 4, Program
Contract No. NASw-703 (NASA)

Dear Mr. Chase:

This letter is a statement of progress during the fourth month of the MIROS contract which covered the period from 20 August to 20 September 1963. This period covered the analytical division of the MIROS program in accordance with the contract schedule. Also preparatory steps were taken for the experimental program phase which will begin next period.

1. Work Accomplished

During the preceeding period analysis of the MIROS schemes continued. One analysis, that covered the mercury system, is included in this report. The others are deferred until later reports. A new MIROS scheme involving F center modulation was introduced and will be investigated during the experimental phase. It is essentially a variation of the original MIROS scheme and represents an attempt to increase modulation rates.

Extensive preparations for the experimental phase have begun. These preparations include both the mercury scheme and the F center method. At present, all the necessary equipment for the mercury experiment has been ordered and the

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XEROX $ 1.60 ph.

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necessary equipment for the F center crystals is being ordered. We find that it may be necessary to produce our own F center crystals. This is not expected to raise any difficulties as there are adequate facilities at Air Arm for this work.

The analysis below is not intended to be a complete statement of the mercury Absorption cell problem. It should however give an indication of the approach to the mercury scheme.

2. Analysis of the Mercury Cell MIROS Element

In this analysis, which is preliminary to the experimental work, it will be assumed that the receiver beam will be continuously incident on the MIROS element. An examination of an energy level diagram of mercury reveals that five energy levels (6^1S_0, 6^3P_2, 6^3P_0, 6^3P_1 and 7^3S_1) need to be considered. The intercombination transition 7^3S_1-6^1P_1 is sufficiently improbable to neglect in comparison to the three strong lines, 7^3S_1-6^3P_2 (5461Å), 7^3S_1-6^3P_1 (4358Å) and 7^3S_1-6^3P_0 (4047Å). These five levels will be numbered from one to five corresponding to ascending energy.

The rate equations governing transistions between these five levels are

$$\dot{n}_1 = -I_T B_{13} n_1 + \{I_T B_{31} n_3 + A_{31} n_3\} + L_1$$

$$\dot{n}_2 = \gamma n_3 - \{I_R B_{25} + L_2\} n_2 + \{A_{52} + I_R B_{52}\} n_5$$

$$\dot{n}_3 = -\{A_{31} + \gamma + L_3 + I_T B_{31}\} n_3 + I_T B_{13} n_1 + A_{53} n_5$$

$$\dot{n}_4 = A_{54} n_5 - L_4 n_4$$

$$\dot{n}_5 = I_R B_{25} n_2 - \{A_{54} + A_{53} + A_{52} + L_5\} n_5$$

where I_t is the total transmitter energy density incident on the cell,

I_R is the total receiver energy density incident on the cell,

B_{12} and B_{25} are the Einstein coefficients of induced emission,

the A's are the Einstein coefficients for spontaneous emission,

γ is the quenching rate per atom from the state $^3P_1$ to the state $^3P_0$,

the n's are the number densities of atoms in the states 1, 2, 3, 4, 5 and the L's represent population changes due to other random causes.

These equations might apply for instance to a system in which the receiver optical energy is modulated by an off-on transmitter signal which at time t=0 is turned on. The initial condition is then that the initial energy level distribution follows the Boltzmann distribution, if transitions between upper states due to the receiver beam are neglected. This assumption is certainly reasonable since the population ratio between ground and excited state will be quite minute, resulting in practically no upper level population (of the order e^{-100}).

The objective in solving these rate equations is of course, to determine the absorption of the 4047 beam, and since the absorption coefficient is proportional to the number density of atoms in the 6^3P_0 state, it is necessary to determine this number density from the rate equations. The absorption coefficient, k, is proportional to the spectral line shape, which in the case of both the 2537Å and 4047Å lines at low gas pressures, is doppler and is therefore of the form:

$$k = \frac{2}{\Delta\nu_D}\sqrt{\frac{\ln 2}{\pi}}\ \frac{\lambda_0^2 g_2 n_2}{8\pi g_1 \tau}\ e^{-\left[\frac{2(\nu-\nu_0)}{\Delta\nu_D}\sqrt{\ln 2}\right]^2}, \text{ where}$$

$$\Delta\nu_D = \frac{2\sqrt{2R\ln 2}}{c}\ \nu_0\sqrt{T/M}\ , \text{ where}$$

ν = the line frequency,

T = the absolute temperature,

M = the molecular weight,

C = the velocity of light,

Also g_2 and g_1 are the upper and lower levels respectively involved in the radiative transition of wavelength, λ_0 ,

n_2 = the number density of atoms, and

τ = the natural lifetime of the upper state.

The transmission of the 4047Å line can then be written as

$$T = \int_{-\infty}^{\infty} e^{-k(\nu)\ell} \times I(\nu)\,d\nu \Big/ \int_{-\infty}^{\infty} I(\nu)\,d\nu = \int_{-\infty}^{\infty} e^{-A(\omega)n_2\ell} \times I(\nu)\,d\nu \Big/ \int_{-\infty}^{\infty} I(\omega)\,d\nu$$

where ℓ is the absorption cell length, and the expression for the absorption coefficient has been separated into two terms so that the linear dependence of absorption on the number density of atoms is easily seen. The value of n_2 at any time will then be obtained from a solution of the rate equations. See Figure 1.

Since the creation of $^3P_0$ levels depends on collisions of excited atoms (in the $^3P_1$ state) with the quenching gas it is necessary to determine the collision probability for the transition $^3P_1 \rightarrow {}^3P_0$. The relevant formula is given from Kinetic theory and is:

$$Z(T,\sigma) = 2Nn_2\sigma^2\sqrt{2\pi RT\left(\frac{1}{M_1}+\frac{1}{M_2}\right)}$$

$Z(T,\sigma)$ is the number of collisions per second per unit volume,

N & n_2 are concentrations of the two gasses,

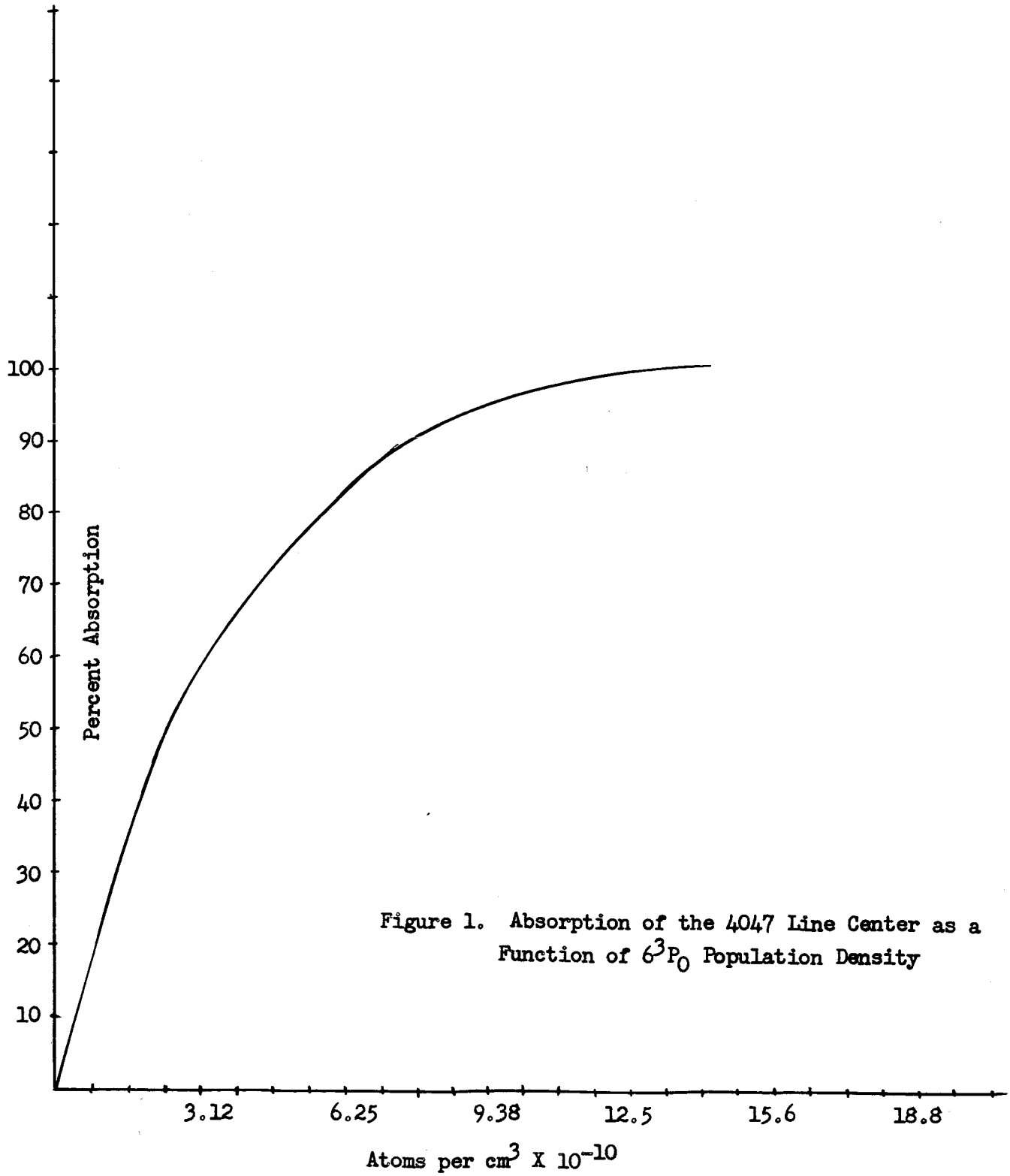

Figure 1. Absorption of the 4047 Line Center as a Function of 6^3P_0 Population Density

TABLE I

Transition	Wavelength (Å)	Lifetime (sec)	A Coefficient $(sec)^{-1}$	B/A (tm^2/erg)	g (ratio)
$6^3P_1 - 6^1S_0$	2537	1.1×10^{-7}	9×10^6	1.2×10^2	3
$7^3S_1 - 6^3P_0$	4047	7×10^{-9}	1.4×10^8	1.9×10^2	3
$7^3S_1 - 6^3P_2$	5461	1.3×10^{-8}	7×10^7	2.4×10^2	3/5
$7^3S_1 - 6^3P_1$	4358	8.2×10^{-9}	1.2×10^8	2.0×10^2	1

TABLE II

Quenching Gasses Available for the MIROS System

Foreign Gas	Quenching Process	Available Energy	Required Energy	Energy Difference	σ^2 $X10^{16} cm^2$
N_2	$Hg(6^3P_1) + N_2 \rightarrow Hg(6'S_0) + N_2'$	.218	.228	-.070	.274
H_2O	$Hg(6^3P_1) + H_2O \rightarrow Hg(6'S_0) + H_2O'$	.218	.197	.021	1.43
NO	$Hg(6^3P_1) + NO \rightarrow Hg(6'S_0) + NO'$	.218	.231	-.013	35.3
CO_2	$Hg(6^3P_1) + CO_2 \rightarrow Hg(6'S_0) + CO_2'$	.218	.238	-.020	3.54
NH_3	$Hg(6^3P_1) + NH_3 \rightarrow Hg(6'S_0) + NH_3'$	.218	.202	.016	4.20

* N_2' denotes excited Nitrogen, etc.

σ is the cross section for the quenching transition,

R is the gas constant,

T is the absolute temperature, and

M_1 & M_2 are the molecular weights of the two gasses.

The number density of the quenching gas can be obtained from the ideal gas formula since only low gas pressures will be present in the gas cell. This number density is the same for all gasses and is 9.61×10^{18} P/T moles/c.c., where the pressure is expressed in millimeters of mercury and T is the absolute temperature.

It is now possible after a determination of the Einstein A and B coefficients to obtain a numerical answer for n_2. The Einstein A coefficients are easily calculated and the B coefficients are related by the equation:

$\frac{A_{21}}{B_{21}} = \frac{2h\nu^3}{c^2}\frac{g_1}{g_2}$, ν = the line frequency,

c = the velocity of light, and

g_1 & g_2 are the statistical weights of the levels 1 & 2;

also $B_{21}/B_{12} = g_1/g_2$.

Table I lists data on the Einstein coefficients for the mercury transitions.

It is also necessary to know the value of the quenching cross sections for the creation of the 6^3P_0 metastable state. Some values of the quenching cross section, are given along with the corresponding gasses in Table II. This together with the molecular weights, temperature and partial pressures will enable a calculation of γ to be made. Hence

$$Z = \gamma n = 2\sigma_Q^2 N n_2 \sqrt{2RT\left(\frac{1}{M_1}+\frac{1}{M_2}\right)}$$

$$= 2 \times 27.4 \times 10^{-19} \times 3.00 \times 10^{17} \sqrt{6.28 \times 8.31 \times 10^7 \times 300\left[\frac{1}{200}+\frac{1}{14}\right]}$$

$$= 1.96 \times 10^6 n_2 \quad \frac{\text{quenching collisions}}{\text{sec-cm}^3}$$, when nitrogen at a

pressure of 10 mm Hg and temperature of 300°K has been used as the quenching gas.

The only remaining quantities to be evaluated are the L's and these are by definition empirical, therefore must either be estimated or in a first order treatment, neglected. The solution of these five linear differential equations is complicated and not very revealing. Therefore, as always in similar cases, a simpler approach based on insight into the problem, is desired. It is evident for instance that the population of the ground state (6^1S_0) will be much larger than that of the first excited state (6^3P_1), therefore the number of upward transitions will greatly exceed the number of downward transitions at least for the low intensity and short times considered. The net population change of the first excited level due to transitions from the ground state is $I_T B_{13} n_1 - I_T B_{31} n_3 - A_{31} n_3 = I_T B_{13} n_1\left[1 - \frac{g_1}{g_3}\frac{n_3}{n_1}\right] - A_{31} n_3 \sim I_T B_{13} n_1 - A_{31} n_3$ since $n_3 \ll n_1$. From both theoretical and physical results, $A_{31} \sim 10^{-7}$ sec. while from an earlier discussion, $\gamma \sim 10^{-6}$, hence an estimate of the number of spontaneous transitions downward occurs at about 10 times the rate as that for quenching collisions.

Theory and experiment also gives, in good agreement, a value for the absorption coefficient of the Mercury 2537Å line (at the line center); $k_o = 1.31 \times 10^{-13} n_1$ cm^{-1} ; and since the vapor pressure at 20°C is 1.2 X 10^{-3} mm Hg

$n_1 = 3.94 \times 10^{13}$ atoms/c.c. Therefore an absorption cell 1 cm long will absorb 99.4% of the incident radiation. If one-tenth of this is converted to the metastable state (6^3P_0), roughly one-tenth of the number of incident photons will be absorbed.

Suppose W milliwatts/cm^2 are incident on a cm. long absorption cell, then $N = \frac{W\Delta t}{h\nu}$ photons will be absorbed in a time, Δt, on the average. This information will yield an estimate of the amount of power necessary to create a sufficiently high absorption for the 4047 line. From the formula for k_o (4047Å) a numerical value for this quantity is k_o (4047Å) = 12.8×10^{-12} n_2 cm^{-1}. Based on these ideas an estimate of the amount of incident power required to increase the absorption of the 4047Å line to some value, say 50% can be made by setting $1 \times 12.8 \times 10^{-12} \times n_2 = .693$; or $n_2 = 5.42 \times 10^{10}$ atoms/c.c. in the (6^3P_0) state. Hence

$$W = \frac{6.62 \times 10^{-34} \times 4.18 \times 10^{15} \times 5.42 \times 10^{10} \times 10}{\Delta t}$$

or $\frac{4.22 \times 10^{-4}}{\Delta t}$ milliwatts. Whence if it is desired to obtain 50% absorption in .1 millisecond, 4.22 milliwatts of energy density are required. Figure 2 shows some further relations between incident power, time and absorption.

It is understood that this preliminary analysis is not intended to be complete, and that more thorough analyses will appear in later reports.

3. PLANS FOR NEXT PERIOD

During the next period it is expected that at least two MIROS schemes will be prepared for experimental work. These two schemes are (1) the mercury absorption cell scheme, and (2) the Alkalai Halide F center schemes. As stated

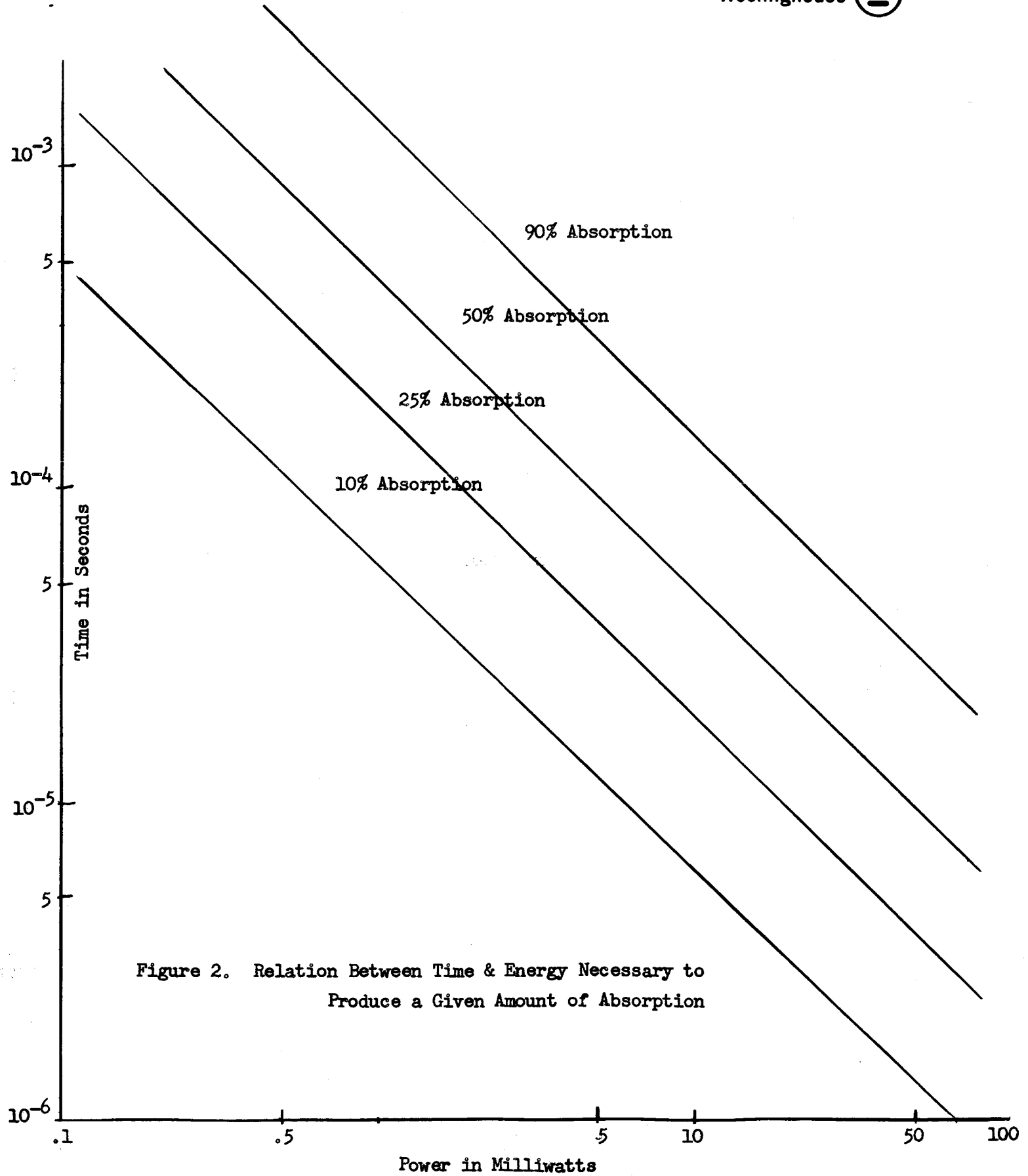

Figure 2. Relation Between Time & Energy Necessary to Produce a Given Amount of Absorption

in an earlier report further experiments will be deferred until these two are well underway since it is more efficient to concentrate efforts especially at the beginning of the experimental work. As usual, analysis and research will continue on all schemes in addition to concurrent experimental efforts.